TFAWS 2009
Orion Project
Alternate Attitude Study

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GRC, JSC, ESCG

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14-August-2009

Presentation Topics

- Introduction/Analysis purpose
- Model Overview
  - Model geometry
  - Analysis assumptions
  - Vehicle Configuration
- Attitudes Analyzed
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- Results
  - Heater power results
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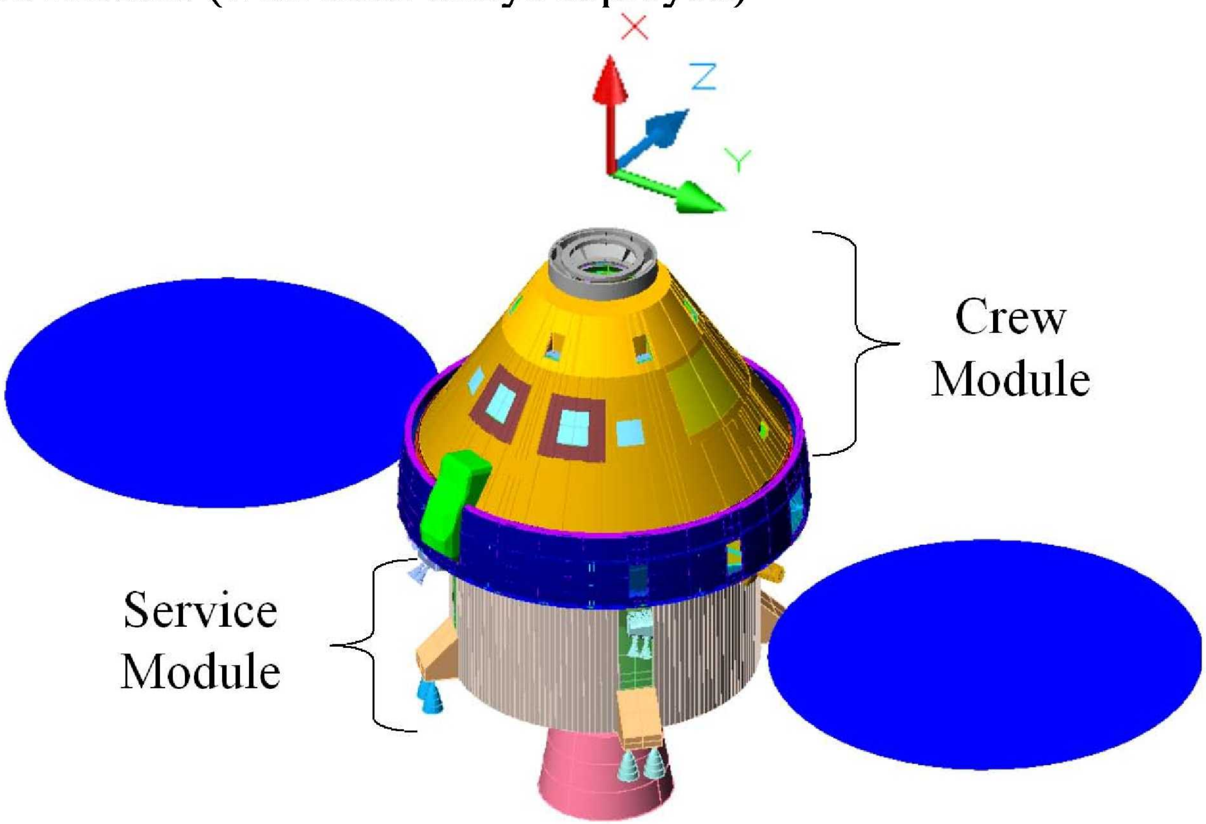
- Conclusions

Analysis Purpose

- The Orion project is being heavily analyzed in baseline attitudes by all subsystems (Power, Comm, Thermal, etc.)
- Project management wanted to know how the vehicle performed in various alternate attitudes
  - Determine if attitudes other than the baseline perform better from an overall vehicle perspective
  - Provide operational flexibility
- This analysis focused on the thermal performance of the vehicle in these alternate attitudes.
  - Pressure vessel (PV) heater power
    - Used to prevent condensation on interior, habitable variables
  - Other vehicle heaters
  - Radiator sink temperature

Model Geometry

- Orion prime contractor (Lockheed Martin) developed an integrated vehicle model for the Orion Design Analysis Cycle 2.
- The model is an on-orbit model consisting of:
  - Crew Module
  - Service Module (with solar arrays deployed)



Analysis Assumptions

- All analyses are limited to Low Earth Orbit (LEO).
- Solution Routines
  - Steady State solution, followed by a 10-20 hour transient run.
- Beta Angles
  - Limited to $\beta = 0°$, 15° and 30°.
    - Vehicle is most power limited for these beta angles
    - The vehicle performance was assumed symmetric about $\beta = 0°$.
- Natural Environments
  - Defined by the Orion project's *Design Specification for Natural Environments* (DSNE) document.
  - For solar albedo, a solar zenith angle (SZA) correction was added per the DSNE.

	Cold Case Constants	Hot Case Constants
Albedo	0.17 + SZA Correction	0.28 + SZA Correction
Planetary IR	217 W/m^2	258 W/m^2
Solar Flux	1322 W/m^2	1414 W/m^2
Altitude	460 km	185 km

Crew Exploration Vehicle Project Office

Vehicle Configuration

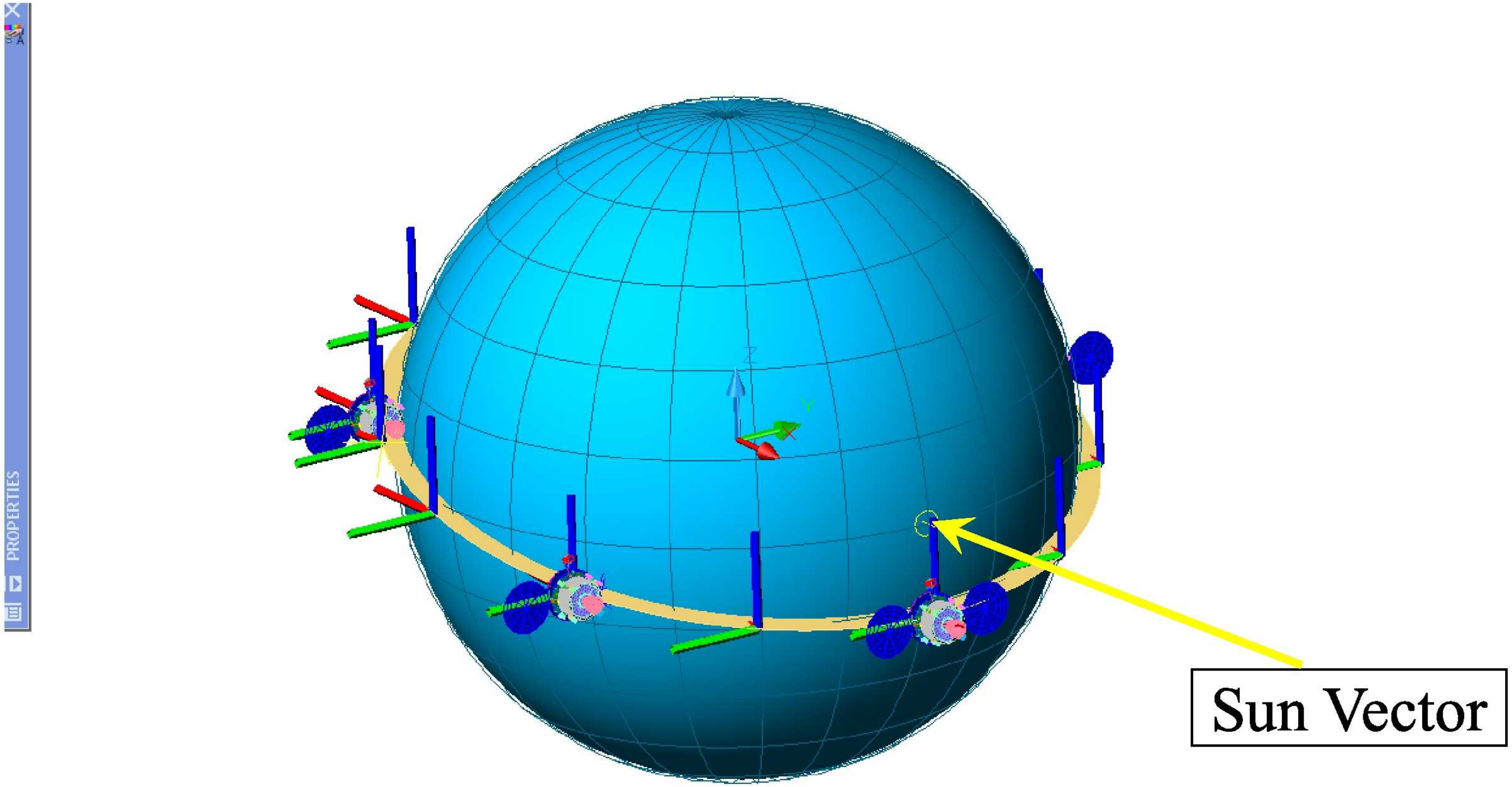
- Two separate power configurations were defined.
  - Phase 90: Nominal vehicle configuration
  - Phase 95: Assumed power failure
- The logic for the ATCS operation also needed to be adjusted based on the power Phase.
  - Phase 90: Nominal flowrates through ATCS loops
  - Phase 95: Increased flowrates to account for increased pump speed in remaining operational loops.
- A final vehicle configuration either permitted or prevented flow to ATCS loops integrated into the Pressure Vessel to assist with condensation prevention (known as S-Loops).
  - Nominally, this option was "off," but was activated for some special additional cases.

Attitudes Considered

- The analysis considered five different attitudes, including the baseline attitude
  - Baseline attitude of Aft-to-Sun (ATS)
  - Nose Forward
  - Yaw Steering
  - +Y-axis Tumble
  - Broadside Sun
    - +Z to sun
    - Flipping +Z/-Z every orbit
    - Flipping +Z/-Z every 4th orbit

Aft-to-Sun Attitude (Baseline)

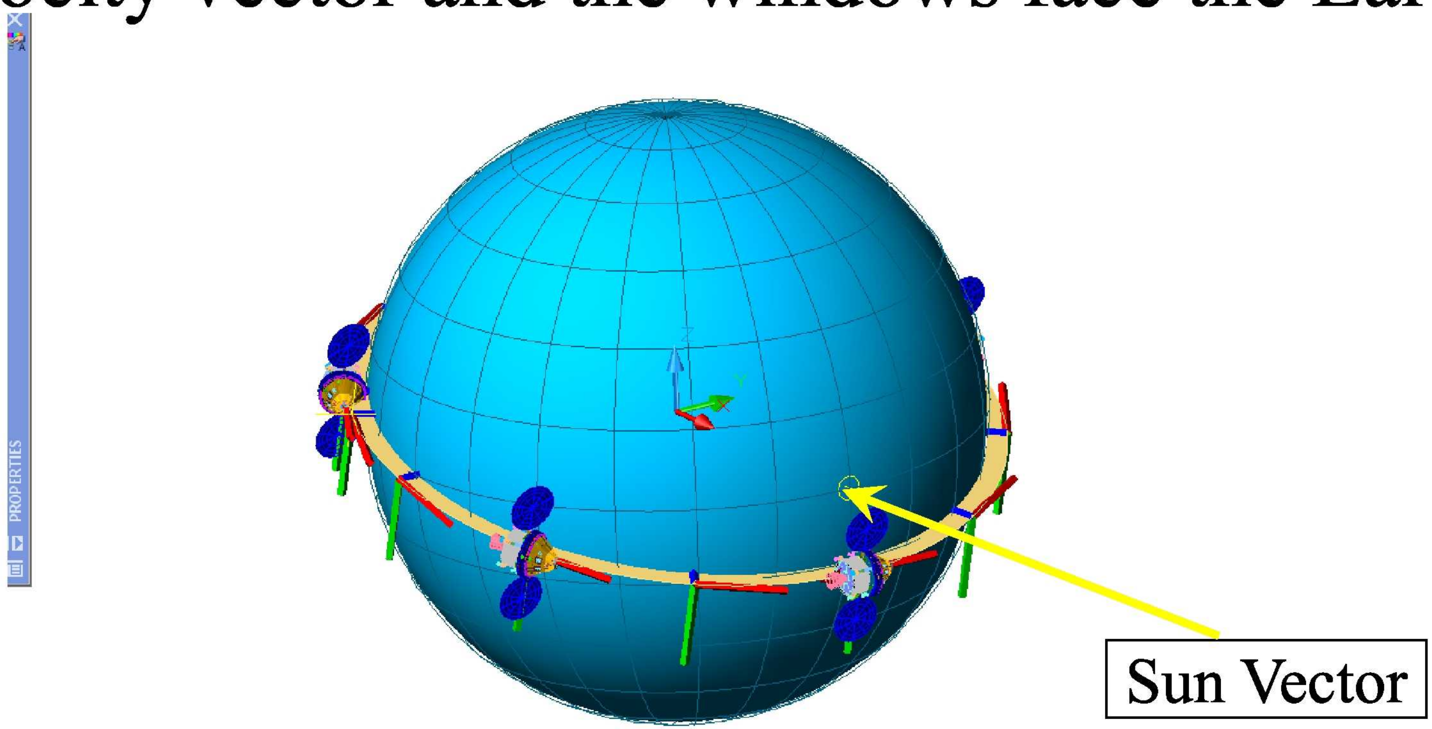
- Baseline inertial attitude with the Orion Main Engine facing the sun.



Beta = 15

Nose-to-Sun Attitude

- A Local Vertical/Local Horizontal (LVLH) attitude in which the nose of the CM is on the velocity vector and the windows face the Earth.



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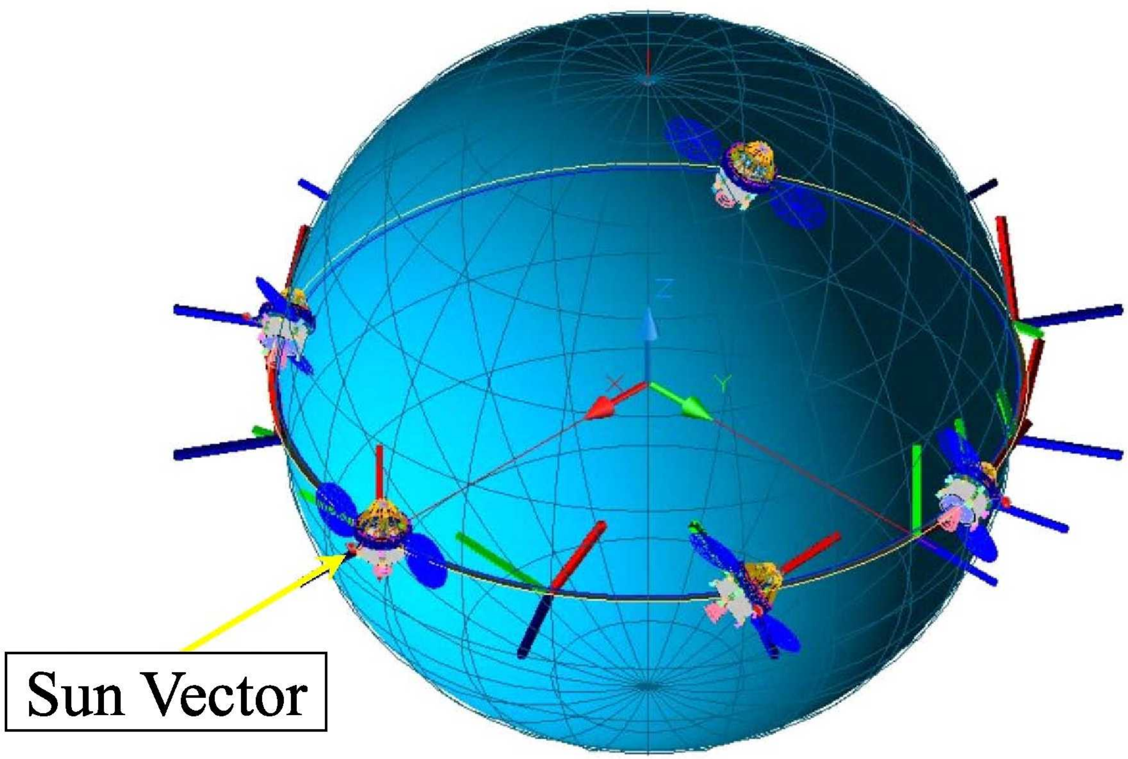
Yaw-Steering Attitude

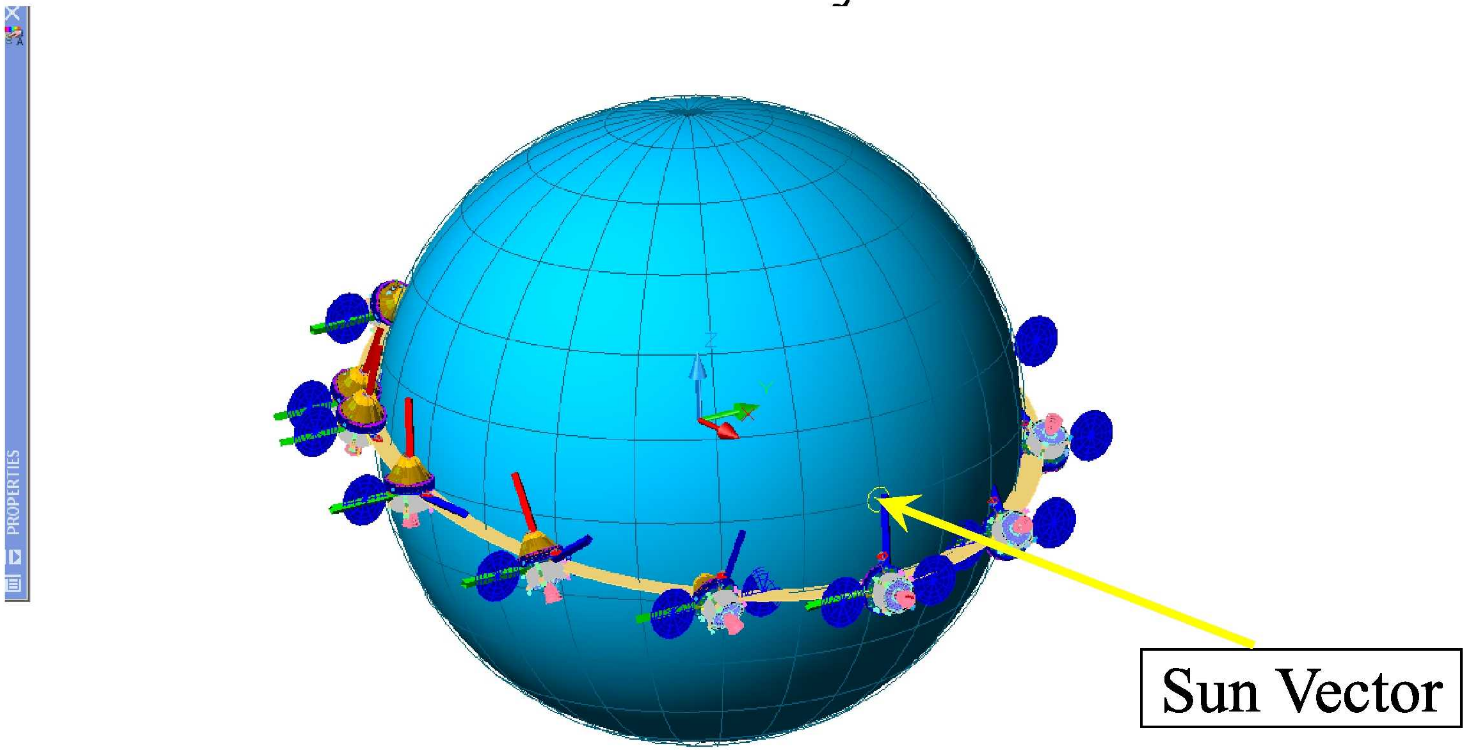
- A modified LVLH attitude in which the yaw is altered throughout the course of the orbit to maximize solar array illumination.



Beta = 0

+Y-Tumble Attitude

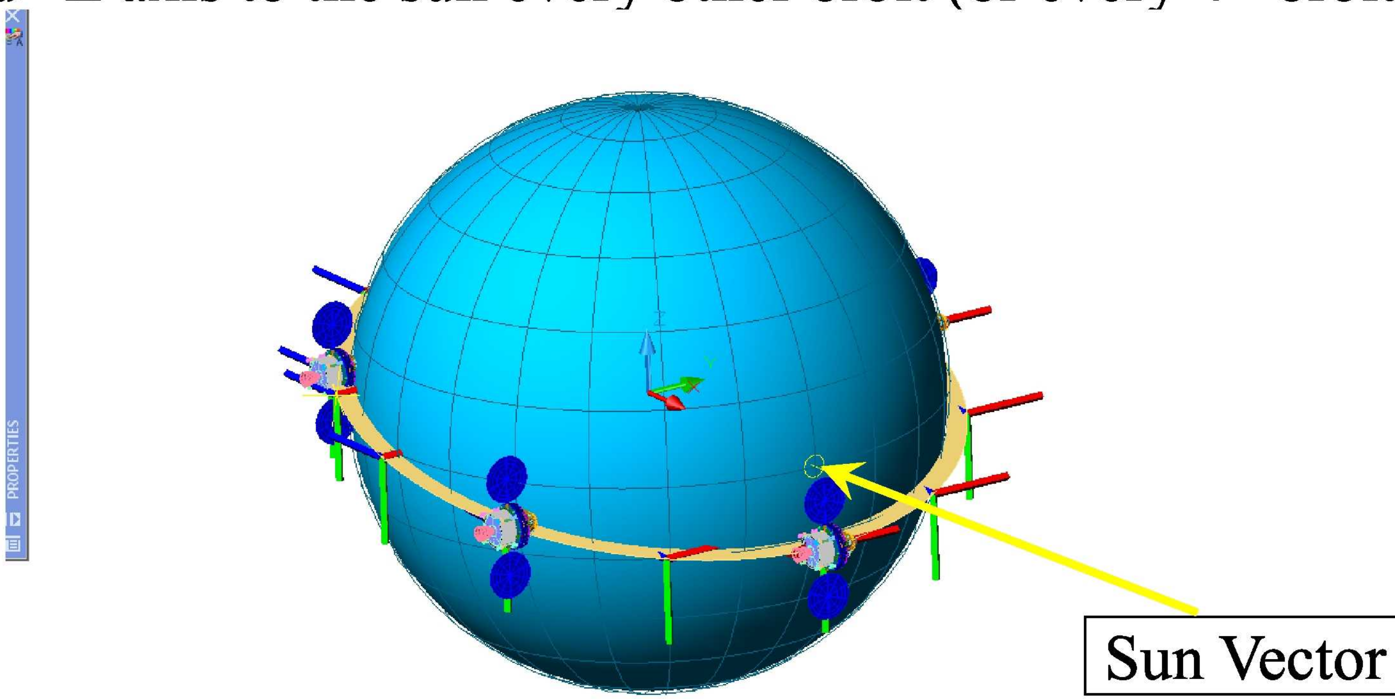
- An inertial attitude where Orion rolls about its Y-axis twice per orbit and the OME faces the sun at solar noon with the +Y-axis on the velocity vector.



Beta = 15

Broadside-to-Sun Attitude

- An inertial attitude with the +Z-axis of Orion facing the sun at solar noon.
  - Flip-Flop: Same as the basic BSS, but alternates facing the +Z and –Z axis to the sun every other orbit (or every 4th orbit).



Beta = 15

Case Matrix

- Each orientation/attitude required 12 cases to capture all combinations of Power and Environment.
- Also ran an additional 8 cases with the S-Loops active were run for select cases.
- Example for Yaw Steering:

Case Number	Case Name	Z_Mission_Orbit DSNE Environment Bias	PEL Phase	Orbital Altitude	Beta	Inner ATCS Flow Rate (lb/hr)	Outer ATCS Flow Rate (lb/hr)
1	LEO_YS_Cold_90_B00	LEO_ISS_Cold	90	460km	0	320	837
2	LEO_YS_Cold_90_B15	LEO_ISS_Cold	90	460km	15	320	837
3	LEO_YS_Cold_90_B30	LEO_ISS_Cold	90	460km	30	320	837
4	LEO_YS_Cold_95_B00	LEO_ISS_Cold	95	460km	0	428	1116
5	LEO_YS_Cold_95_B15	LEO_ISS_Cold	95	460km	15	428	1116
6	LEO_YS_Cold_95_B30	LEO_ISS_Cold	95	460km	30	428	1116
7	LEO_YS_Hot_90_B00	LEO_ISS_Hot	90	185km	0	320	837
8	LEO_YS_Hot_90_B15	LEO_ISS_Hot	90	185km	15	320	837
9	LEO_YS_Hot_90_B30	LEO_ISS_Hot	90	185km	30	320	837
10	LEO_YS_Hot_95_B00	LEO_ISS_Hot	95	185km	0	428	1116
11	LEO_YS_Hot_95_B15	LEO_ISS_Hot	95	185km	15	428	1116
12	LEO_YS_Hot_95_B30	LEO_ISS_Hot	95	185km	30	428	1116

Heater Results

- All cases were compared against the baseline case of Aft-to-Sun
- The change in heater power was calculated by the following simple formula:

$$Heater\ Power\ Change = \frac{Power_{Alt\ Att} - Power_{Baseline}}{Power_{Baseline}} * 100\%$$

- Therefore, a negative Heater Power Change indicates less heater power is used in the alternate attitude.

Aft-to-Sun Heater Results

- Results for the Aft-to-Sun heater power are shown in the table below to provide the baseline comparison numbers.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)
LEO_ATS_Cold_B00_P90	1282	993
LEO_ATS_Cold_B15_P90	1275	991
LEO_ATS_Cold_B30_P90	1268	998
LEO_ATS_Cold_B00_P95	1235	994
LEO_ATS_Cold_B15_P95	1233	994
LEO_ATS_Cold_B30_P95	1227	1002
LEO_ATS_Hot_B00_P90	820	717
LEO_ATS_Hot_B15_P90	821	719
LEO_ATS_Hot_B30_P90	842	741
LEO_ATS_Hot_B00_P95	809	721
LEO_ATS_Hot_B15_P95	810	725
LEO_ATS_Hot_B30_P95	836	748

Yaw-Steering Heater Results

- Heater power needs are less than Aft-to-Sun, especially at higher beta angles.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_YS_Cold_90_B00	1195	911	-7%	-8%
LEO_YS_Cold_90_B15	1131	828	-11%	-16%
LEO_YS_Cold_90_B30	1086	728	-14%	-27%
LEO_YS_Cold_95_B00	1178	916	-5%	-8%
LEO_YS_Cold_95_B15	1115	833	-10%	-16%
LEO_YS_Cold_95_B30	1063	730	-13%	-27%
LEO_YS_Hot_90_B00	865	673	5%	-6%
LEO_YS_Hot_90_B15	817	596	0%	-17%
LEO_YS_Hot_90_B30	820	518	-3%	-30%
LEO_YS_Hot_95_B00	840	677	4%	-6%
LEO_YS_Hot_95_B15	791	602	-2%	-17%
LEO_YS_Hot_95_B30	788	519	-6%	-31%

Nose Forward Heater Results

- Saves heater power (35%) and overall vehicle heater power (up to 25%) as compared to ATS.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_NF_Cold_P90_B0	860	531	-33%	-47%
LEO_NF_Cold_P90_B15	869	543	-32%	-45%
LEO_NF_Cold_P90_B30	898	564	-29%	-43%
LEO_NF_Cold_P95_B0	848	538	-31%	-46%
LEO_NF_Cold_P95_B15	852	548	-31%	-45%
LEO_NF_Cold_P95_B30	880	568	-28%	-43%
LEO_NF_Hot_P90_B0	535	335	-35%	-53%
LEO_NF_Hot_P90_B15	557	348	-32%	-52%
LEO_NF_Hot_P90_B30	589	370	-30%	-50%
LEO_NF_Hot_P95_B0	512	338	-37%	-53%
LEO_NF_Hot_P95_B15	512	349	-37%	-52%
LEO_NF_Hot_P95_B30	553	374	-34%	-50%

+Y-Tumble Heater Results

- There is a reduction in PV heater power (>50%) and overall vehicle heater power (>38%) in for all beta angles.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_Y-Tumb_Cold_B00_P90	790	434	-38%	-56%
LEO_Y-Tumb_Cold_B15_P90	779	426	-39%	-57%
LEO_Y-Tumb_Cold_B30_P90	766	414	-40%	-59%
LEO_Y-Tumb_Cold_B00_P95	778	443	-37%	-55%
LEO_Y-Tumb_Cold_B15_P95	773	438	-37%	-56%
LEO_Y-Tumb_Cold_B30_P95	757	424	-38%	-58%

BSS Heater Results

- PV heater power (50% reduction) and overall heater power (37% reductions) is lower as compared to ATS cold case.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_BSS_Cold_B00_P90	802	494	-37%	-50%
LEO_BSS_Cold_B15_P90	795	491	-38%	-50%
LEO_BSS_Cold_B30_P90	789	490	-38%	-51%
LEO_BSS_Cold_B00_P95	771	498	-38%	-50%
LEO_BSS_Cold_B15_P95	764	493	-38%	-50%
LEO_BSS_Cold_B30_P95	754	490	-39%	-51%
LEO_BSS_Hot_B00_P90	469	315	-43%	-56%
LEO_BSS_Hot_B15_P90	468	318	-43%	-56%
LEO_BSS_Hot_B30_P90	481	325	-43%	-56%
LEO_BSS_Hot_B00_P95	433	313	-46%	-57%
LEO_BSS_Hot_B15_P95	434	316	-46%	-56%
LEO_BSS_Hot_B30_P95	389	310	-53%	-59%

BSS Flip Flop Heater Results

- Heater savings for both PV (55%) and overall vehicle (45%) are larger for flip flop case.
  - Flip Flop does reduce heater power needs from pure BSS orientation.
  - No real thermal difference between flipping every orbit or every 4th orbit.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_BSS_Flip_1_Orb_Cold_B00_P90	707	438	-45%	-56%
LEO_BSS_Flip_1_Orb_Cold_B15_P90	697	438	-45%	-56%
LEO_BSS_Flip_1_Orb_Cold_B30_P90	684	431	-46%	-57%
LEO_BSS_Flip_1_Orb_Cold_B00_P95	677	449	-45%	-55%
LEO_BSS_Flip_1_Orb_Cold_B15_P95	670	444	-46%	-55%
LEO_BSS_Flip_1_Orb_Cold_B30_P95	655	437	-47%	-56%
LEO_BSS_Flip_1_Orb_Hot_B00_P90	364	254	-56%	-65%
LEO_BSS_Flip_1_Orb_Hot_B15_P90	367	255	-55%	-65%
LEO_BSS_Flip_1_Orb_Hot_B30_P90	370	255	-56%	-66%
LEO_BSS_Flip_1_Orb_Hot_B00_P95	339	255	-58%	-65%
LEO_BSS_Flip_1_Orb_Hot_B15_P95	340	258	-58%	-64%
LEO_BSS_Flip_1_Orb_Hot_B30_P95	342	260	-59%	-65%

Cases with S-Loops Active

- All cases with S-Loops show improvement from non-S-Loop cases.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_YS_Cold_90_B00_S-Loop	893	619	-30%	-38%
LEO_YS_Cold_90_B15_S-Loop	836	541	-34%	-45%
LEO_NF_Cold_P90_B0_S-Loop	637	293	-50%	-70%
LEO_NF_Cold_P90_B15_S-Loop	640	302	-50%	-70%
LEO_BSS_Cold_B00_P90_S-Loop	658	339	-49%	-66%
LEO_BSS_Cold_B15_P90_S-Loop	652	339	-49%	-66%
LEO_BSS_Cold_B00_P95_S-Loop	665	383	-46%	-61%
LEO_BSS_Cold_B15_P95_S-Loop	660	380	-46%	-62%

Heater Summary

- In LEO, low Beta (<30°), the Aft-to-Sun attitude requires the most PV and total vehicle heater power of all attitudes considered.
  - All other attitudes offer heater savings in the cold environments.
  - Some Hot environments show a small increase in heater power.

Radiator Sink Temp Calculation

- Applied a simple method to perform a first level comparison of the various attitudes
- The sink temperatures for 8 panels were combined using a T^4 average at each time step
- A W/m^2 value was then calculated for each case representing the heat rejection per area
  - It is conceded that this averaging technique dilutes the effect of the cyclic pattern of the orbit sink temperature, and assumes that the ATCS provides the correct fluid temperature throughout the vehicle
- Provides a first level overall heat rejection capability that can be used to compare different attitudes.

Radiator Sink Temp Calculation

- Results show that the Power Phase made virtually no difference in the sink temperature prediction.
- The different flow rates between the phases will change the resultant W/m^2 calculated between the two phase
  - The general comparison of attitude effects within the same phase has the same result.
- Therefore, only the Phase 90 data will be presented.

Radiator Sink Temp Comparison

- Similar to the heater power, a simple calculation was performed to assess the change in radiator performance.

$$Radiator\ Performance\ Change = \frac{\left(\frac{Power}{Area}\right)_{Alt\ Att} - \left(\frac{Power}{Area}\right)_{Baseline}}{\left(\frac{Power}{Area}\right)_{Baseline}} * 100\%$$

- A negative value indicates that the alternate attitude provides less heat rejection than the baseline Aft-to-Sun case.

Cold Case Rad Sink Temp Results

- Only Nose Forward and Y-Tumble provide increased heat rejection capability.

Case Name	W/m^2	% Difference from ATS
LEO_ATS_Cold_B00_P90	2.009	--
LEO_ATS_Cold_B15_P90	2.003	--
LEO_ATS_Cold_B30_P90	1.989	--
LEO_YS_Cold_90_B00	1.813	-10%
LEO_YS_Cold_90_B15	1.791	-11%
LEO_YS_Cold_90_B30	1.849	-7%
LEO_NF_Cold_P90_B0	2.047	2%
LEO_NF_Cold_P90_B15	2.059	3%
LEO_NF_Cold_P90_B30	1.972	-1%
LEO_ATS_Cold_B00_P90_2Tumbles	2.064	3%
LEO_ATS_Cold_B15_P90_2Tumbles	2.062	3%
LEO_ATS_Cold_B30_P90_2Tumbles	2.062	4%
LEO_BSS_Cold_B00_P90	1.652	-18%
LEO_BSS_Cold_B15_P90	1.653	-17%
LEO_BSS_Cold_B30_P90	1.630	-18%
LEO_BSS_Flip_1_Orb_Cold_B00_P90	1.654	-18%
LEO_BSS_Flip_1_Orb_Cold_B15_P90	1.655	-17%
LEO_BSS_Flip_1_Orb_Cold_B30_P90	1.631	-18%

Hot Case Rad Sink Temp Results

- Only Nose Forward provides increased heat rejection capability.

Case Name	W/m^2	% Difference from ATS
LEO_ATS_Hot_B00_P90	1.919	--
LEO_ATS_Hot_B15_P90	1.912	--
LEO_ATS_Hot_B30_P90	1.891	--
LEO_YS_Hot_90_B00	1.718	-11%
LEO_YS_Hot_90_B15	1.705	-11%
LEO_YS_Hot_90_B30	1.724	-9%
LEO_NF_Hot_P90_B0	1.919	0%
LEO_NF_Hot_P90_B15	1.937	1%
LEO_NF_Hot_P90_B30	1.795	-5%
LEO_BSS_Hot_B00_P90	1.507	-21%
LEO_BSS_Hot_B15_P90	1.494	-22%
LEO_BSS_Hot_B30_P90	1.508	-20%
LEO_BSS_Flip_1_Orb_Hot_B00_P90	1.510	-21%
LEO_BSS_Flip_1_Orb_Hot_B15_P90	1.496	-22%
LEO_BSS_Flip_1_Orb_Hot_B30_P90	1.510	-20%

Radiator Sink Temp Summary

- Due to geometry and view to the sun, the Aft-to-Sun baseline attitude provides excellent heat rejection capability.
- The Nose Forward attitude shows comparable results based on the T^4 averaging technique, but most other attitudes show decreased capability.

Conclusions

- Heater Conclusions
  - Aft-to-Sun uses the most heater power of all attitudes considered.
  - Activating the S-Loops provided additional heater power savings.
- Radiator Conclusions
  - Aft-to-Sun and Nose Forward attitudes both provide similar radiator heat rejection.
  - The feasibility of the alternate attitudes will depend on how much load is on the radiators if they are flown.
- Implications for overall vehicle performance
  - As shown by the results for heaters and radiator heat rejection, the a spacecraft's attitude must be a compromise between different systems on the vehicle.
  - No one system will constantly drive the vehicle performance without effecting the capability of the remaining systems..

Backup Material

Solar Zenith Angle Definition

- Solar Zenith Angle is defined as:

$$SZA = \cos^{-1}(\cos(\beta) * \cos(\nu))$$

- β is the beta angle
- ν is the true anomaly

$$\begin{aligned} SZA\ Correction = {} & 4.9115 * 10^{-9} * SZA^4 \\ & + 6.0372 * 10^{-8} * SZA^3 \\ & - 2.1793 * 10^{-5} * SZA^2 \\ & + 1.3798 * 10^{-3} * SZA \end{aligned}$$

BSS Flip Flop Every 4th Orbit Results

- Very similar to flipping every orbit.
  - May require less propellant
- Heater savings for PV is 55% and overall vehicle 43% as compared to ATS cold cases.

Case Name	Avg Vehicle Htr Pwr (W)	Avg PV Htr Pwr (W)	Vehicle Htr Pwr Change	Pressure Vessel Htr Pwr Change
LEO_BSS_Flip_4_Orb_Cold_B00_P90	733	448	-43%	-55%
LEO_BSS_Flip_4_Orb_Cold_B15_P90	731	447	-43%	-55%
LEO_BSS_Flip_4_Orb_Cold_B30_P90	718	441	-43%	-56%
LEO_BSS_Flip_4_Orb_Cold_B00_P95	707	454	-43%	-54%
LEO_BSS_Flip_4_Orb_Cold_B15_P95	699	449	-43%	-55%
LEO_BSS_Flip_4_Orb_Cold_B30_P95	685	442	-44%	-56%